

# Integrating Multiple Space and Ground Sensors to Track Volcanic Activity

Steve Chien<sup>a</sup>, Ashley Davies<sup>a</sup>, Joshua Doubleday<sup>a</sup>, Daniel Tran<sup>a</sup>, Samuel Jones<sup>a</sup>,

Einar Kjartansson<sup>b</sup>, Hróbjartur Þorsteinsson<sup>b</sup>, Kristin Vogfjörð<sup>b</sup>, Magnus Guomundsson<sup>c</sup>, Thor Thordarson<sup>d</sup>, Daniel Mandl<sup>e</sup>

<sup>a</sup>Jet Propulsion Laboratory, California Institute of Technology, USA

<sup>b</sup>Meteorological Office, Iceland

<sup>c</sup>University of Iceland

<sup>d</sup>Edinburgh University

<sup>e</sup>NASA Goddard Space Flight Center, USA

Correspondence author: [steve.chien@jpl.nasa.gov](mailto:steve.chien@jpl.nasa.gov)

**Abstract**—Volcanic activity can occur with little or no warning. Increasing numbers of space borne assets can enable coordinated measurements of volcanic events to enhance both scientific study and hazard response. We describe the use of space and ground measurements to target further measurements as part of a worldwide volcano monitoring system. We utilize a number of alert systems including the MODVOLC, GOESVOLC, US Air Force Weather Advisory, and Volcanic Ash Advisory Center (VAAC) alert systems. Additionally we use in-situ data from ground instrumentation at a number of volcanic sites, including Iceland.

**Keywords:** sensorwebs, volcanoes, solid earth, natural disasters, onboard processing.

## I. INTRODUCTION

The study of volcanoes is important for both scientific and humanitarian reasons. From a scientific standpoint, volcanic gas and ash emissions contribute significantly to the terrestrial atmosphere. Ash depositions and lava flows also can greatly affect local environments. From a humanitarian standpoint many people live within a short distance of active volcanoes and therefore can be affected via both atmospheric (ash, debris) and lava flow phenomena.

Satellite study of volcanoes is very useful because it can provide data for large areas of the Earth's surface with a range of modalities ranging from visible to infra-red, radar and beyond. Satellite sensing can also access remote locations and hazardous regions without difficulty. One issue with space-based volcano measurement is that atmospheric conditions (e.g. clouds) can interfere with many sensors (visible, IR). Additionally, for taskable (e.g., point and shoot) sensors, satellite contention for targets is high (e.g. other targets may be competing for observation time) so that knowledge of specific volcanic activity (e.g. timely alerts) may be required in order to task to acquire volcanic imagery.

In-situ sensing can provide a valuable range of complementary information such as seismographic, discharge, acoustic, and other data. However many volcanoes are not instrumented with in-situ sensors and even those that have sensor networks these are restricted to a relatively small numbers of point sensors. Consequently, ideal volcanic study synergistically combines space and in-situ measurements

This paper describes an effort to integrate space-borne sensing from MODIS (Terra and Aqua), ALI (EO-1), Worldview-2, and in-situ sensing, in an automated scheme to improve global volcano monitoring. Specifically, we describe a “sensorweb” concept in which a number of volcano monitoring systems are linked together to more accurately monitor volcanic activity, and use this activity measurement to automatically task space assets to acquire further satellite imagery of ongoing volcanic activity. We discuss the space and ground sensors and systems and how they are linked together. We also describe results from operations of this system with a focus on the Earth Observing One mission as it has been executing a volcano monitoring campaign for several years now. Finally, we describe analyses of a specific eruption, the Fimmvorduhals-Eyafallajökull eruption in Iceland March-June 2010 as a case study in the potential effectiveness of the sensorweb concept.

## II. VOLCANO EVENT DETECTION USING SPACE AND GROUND SENSORS

Our volcano sensorweb uses a number of volcano monitoring systems to track volcanic activity worldwide. We incorporate the MODIS-MODVOLC and GOES-GOESVOLC satellite-based remote sensing systems include. (MODIS - MODVOLC

The MODIS instrument provides an excellent platform for volcanic activity detection and study. With MODIS instruments flying on both the Terra and Aqua satellites, MODIS provides excellent temporal coverage with 2 daylight and 2 night overflights per 24 hours (with even more frequent coverage at polar targets). The MODIS sensor includes thermal bands with a spectral range of 0.62-14.3  $\mu$  but with moderate spatial resolution of 250m-1000m at IR wavelengths. The MODVOLC system <http://modis.higp.hawaii.edu/> [Wright et al. 2002, 2004] uses a slope fitting method with two MODIS thermal channels to detect and measure thermal emissions for volcanoes. Our sensorweb is linked in to the MODVOLC web site and uses MODVOLC alerts as a central input to trigger volcano observations. The principal limitation of the MODVOLC system is the sensitivity of the MODIS instrument which requires a significant thermal emission to be measurable from space. Further work has enabled site specific algorithmic tuning to enable detection of activity at a finer scale at some additional effort.

The GOESVOLC system utilizes the GOES constellation of geostationary weather satellites to detect volcanic activity. As these sensors are at geostationary orbit altitudes they have lesser sensitivity than low earth orbiting instruments such as MODIS thus are only able to detect major eruptions. However their



Figure 1: Spider Sensor deployed to Mount Saint Helens in 2008 as part of Volcano Sensorweb

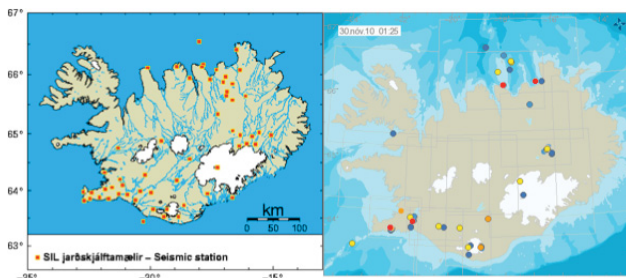


Figure 2a (L): Seismic sensors in Iceland operated by Iceland Met Office, data feed used as part of Volcano Sensorweb.

Figure 2b (R): Detected Earthquake location map automatically derived by Iceland Met Office, integrated as triggers to Volcano Sensorweb

temporal resolution is better with typical update times being at every 15 minutes.

The United States Air Force Weather Advisory System (AFWA) <http://www.afweather.af.mil/index.asp> also distributes weather advisory information regarding volcanic activity with a

focus on aviation hazards. This information typically includes aspects of volcanic activity such as plume location, density, altitude. Our sensorweb utilizes this information as an input to assess volcanic activity.

The worldwide Volcanic Ash Advisory Centers (<http://www.ssd.noaa.gov/VAAC/washington.html>) (VAAC) are nine regional centers that provide aviation related ash hazard information that can be useful at estimating volcanic activity. We subscribe to this information feed and can use it to estimate volcanic activity and trigger follow-on responses.

At various points in time our volcano sensorweb has demonstrated integration with a range of in-situ sensor networks to monitor volcanic activity. Previously we had integrated with Hawaiian Volcano Observatory (HVO) <http://hvo.wr.usgs.gov/> tiltmeter sensors as well as to JPL-deployed SO<sub>2</sub> sensors to demonstrate triggering of space-based observations from in-situ sensor interpretation. We had also demonstrated triggering of response observations based on Mt. Erebus Volcano Observatory (MEVO) <http://erebus.nmt.edu/> in-situ sensing. In 2008-2009 JPL also collaborated with the USGS/CVO and Washington State University to deploy a set of wirelessly networked smart sensors [Huang et al. 2010] to Mount Saint Helens (See Figure 1). These sensors had sophisticated onboard smarts as well as network smarts and ground- to space and space to ground triggering and reconfiguration was demonstrated.

Most recently the volcano sensorweb has been linked up with the sophisticated monitoring network of in-situ sensors at Iceland run by the Iceland Met Office ([www.vedur.is](http://www.vedur.is)). The Iceland Met office has a sophisticated network of sensors to monitor volcanic activity in Iceland including seismographic, strain, GPS, and runoff sensors (see Figure 2). We have demonstrated the ability to trigger space observations from seismic signatures (such as earthquake intensity, location, trending intensity, and shallowing depth). More recently we have been investigating the potential to trigger off of flow rate sensors as many Icelandic volcanoes are glacier-covered so that increases in stream flow rates due to melting ice is often a leading indicator of volcanic activity (see Figure 3).

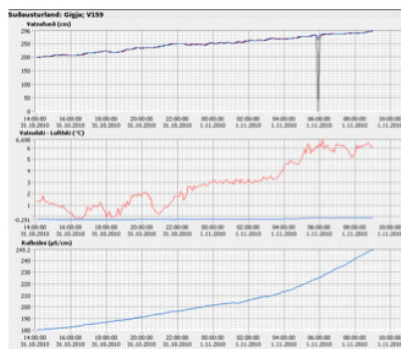
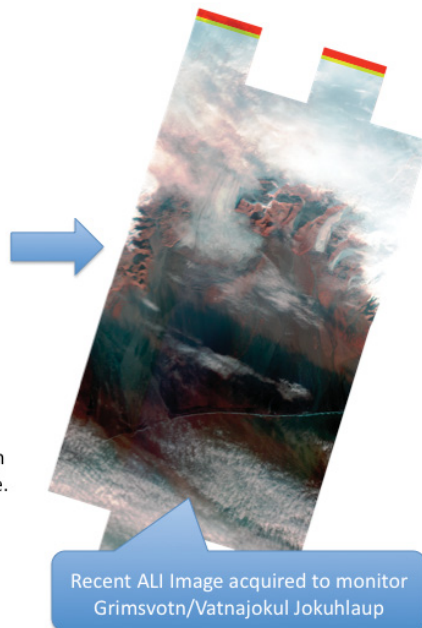


Figure 3: At left, stream gauging information from sensors operated by Iceland Met Office. At right, ALI image acquired (manually) in response to detected Jokuhlaup.



### III. AUTOMATED RESPONSE IMAGERY USING THE EARTH OBSERVING ONE

The Earth Observing One (EO-1) spacecraft has automated tasking capability [Chien et al. 2005, Chien et al. 2010] that enables electronic submission of prioritized observation requests and automated retasking. The sensorweb uses the above alert systems to automatically task volcano observations based on scientist specified observation campaigns. The dataflow of this system is shown below in Figure 4. The sensorweb agents for the monitoring systems (e.g. MODVOLC, GOESVOLC, AFWA...) report the volcanic activity as "science alerts" which specify: location, event type, and other information such as confidence, size, severity, etc. The Science Event Manager processes the alerts and matches them up with scientist defined "observation campaigns" that describe situations in which science alerts or combinations of alerts result in observations

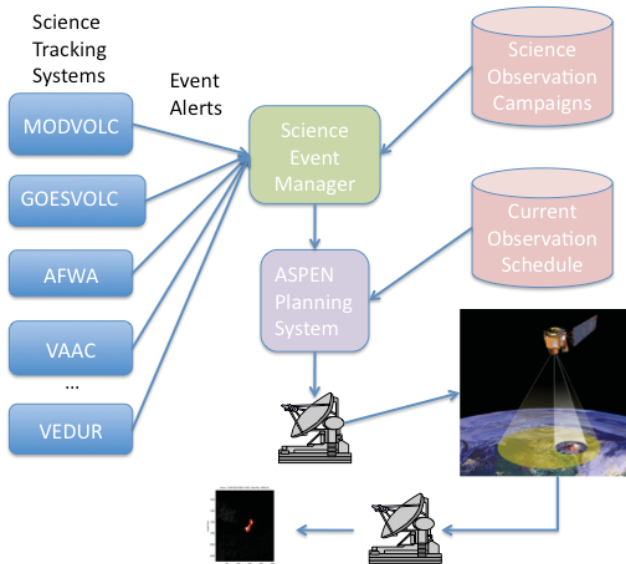


Figure 4: Automated flow from science event alert to observation request to acquired scene to delivered science products.

requests or sets of requests. The EO-1 mission planning system (using the ASPEN system) then attempts to accommodate these observations requests while respecting spacecraft operations constraints and competing observation priorities.

Volcano science campaigns therefore submit requests to EO-1 to image volcanic areas using the Advanced Land Imager (ALI) Instrument (30km wide swath, 30m spatial resolution multispectral, 9 bands 0.4-2.4  $\mu$  spectral range) and Hyperion (HYP) Instrument (7.5km wide swath, 30m spatial resolution hyperspectral, 200 bands 0.4-2.4  $\mu$  spectral range).

#### IV. AUTOMATED ANALYSIS OF REMOTE SENSED VOLCANO IMAGERY AND DATA DELIVERY

After the EO-1 data is acquired it is automatically processed for thermal signature extraction. Specifically, the Hyperion imagery is automatically processed onboard the spacecraft to derive surface temperature estimates using spectral slope estimation techniques [Davies et al. 2006] that can be downlinked very rapidly using engineering channel downlinks.

When the full imagery is downlinked automatic ground processing can derive still further information. On the ground a more complete analysis can provide estimates of volumetric lava effusion rates. In this process, first, hot pixels are identified based on spectral signature (Figure 5). Next, each pixel is fitted to a blackbody radiation curve to derive a hot pixel area and temperature (e.g. an estimate that the pixel consists of a given area at ambient temperature and the remainder at a higher temperature). This process is depicted graphically in Figure 6. Finally, the data from each of these hot pixels are aggregated and matched to a volcanic model that then estimates the lava effusion rate based on the thermal signature, area, heat lossage, and lava composition (Figure 7). We are working on development of additional volcano products, such as an ALI-based plume product.

#### V. IMPACT OF THE EARTH OBSERVING ONE VOLCANO SENSORWEB – A UNIQUE DATASET

The Volcano Sensorweb has been in operation tasking EO-1 for 5 years and has acquired thousands of images. Figure 8 shows the geographic distribution of Volcano Sensorweb targets over the lifetime of the project (2004-present). As a snapshot of typical activity, for Fiscal Year 2010 (October 2009-September 2010) 589 volcanic scenes were acquired with over 249 of these recording an active thermal signature. In the timeframe October-November 2010 there were 987 science alerts broken down by source as indicated in Table 1.

Table 1: Volcano Science Alerts for October – November 2010 by Alert Source	
Alert Source	Number of Alerts
MODVOLC	517
AFWA	459
Iceland VEDUR	9
VAAC	2

The breakdown of alerts for October/November 2010 are shown in Table 2.

Table 2: Volcano Science Alerts or October – November 2010 by Volcano Target	
Number of Alerts	Volcanoes with this number of alerts
50+	Batu Tara, Dukono, Kliuchevskoi, Merapi, Shiveluch
10-49	Ambrym, Bagana, Barren Island, Erebus, Erte Ale 2, Halemaumau HI, Karymsky, Kilauea 2, Manam, Piton de la Fournaise, Popocateptl, Semeru, Tinakula, Tungurahua, Villarrica
1-9	Chaiten, Eyjafjallajokull, Fuego, Grimsvotn, Ibu, Krakatau, Lolobau, Nevado del Huila, Oldoinyo Lengai, Planchon Peteroa, Reventador, Sakura Jima, Sangay, Santa Maria, Soufriere Hills, Stromboli, Sulu Range, Ubinas, Yasur.

The recent 2010 eruptions of Eyjafjallajokull provides an excellent analysis case for sensorweb operations. Between 24 March 2010 and 5 June 2010 50 EO-1 acquisitions of the volcano were completed. However, many other space-borne sensors can and did acquire data of the eruption. An analysis [Jones 2010] showed that at least 18 spacecraft with relevant instrumentation had an average of 40 overflights per day with approximately half of the assets being nadir imaging and the other half requiring point and shoot tasking. Taking into account only geometric viewing constraints this produces and estimate of over 1000 imaging opportunities.

#### VI. CONCLUSIONS

We have described a networking of science tracking, automated tasking, and data analysis systems into a sensorweb to enable global monitoring of volcanoes. This technique has enabled timely monitoring of unpredictable, varied, and short-lived volcanic activity.



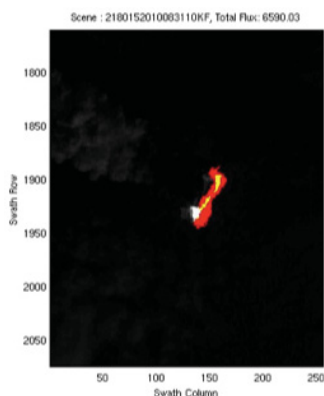


Figure 5: Ground automatic processing – identification of hot pixels based on thresholding.

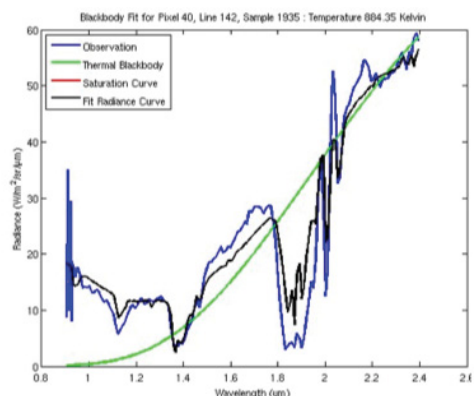


Figure 6: Ground automatic processing – fit of each pixel to temperature and area, based on blackbody curve fit

#### Parameters:

**Mass Effusion rate:** 6590.03 kg/s  
**Volumetric Effusion rate:** 2.64 m³/s  
**Total Power loss:** 1.98e+09 W  
**Radiative Power loss:** 1.61e+09 W  
**Convective Power loss:** 3.66e+08 W  
**Total effective area :** 7.98e+04 m²  
**Effective temperature:** 7.73e+02 K  
**Look Angle:** 12.63 deg.  
**Range to Ground:** 705.85 km

Figure 7: Ground automatic processing – using each pixel to temperature and area, estimate total lava effusion rate based on model

#### ACKNOWLEDGMENTS

Portions of this work were performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract from the National Aeronautics and Space Administration.

#### REFERENCES

- S. Chien, R. Sherwood, D. Tran, B. Cichy, G. Rabideau, R. Castano, A. Davies, D. Mandl, S. Frye, B. Trout, S. Shulman, D. Boyer, "Using Autonomy Flight Software to Improve Science Return on Earth Observing One," *Journal of Aerospace Computing, Information, and Communication*, Apr. 2005, pp. 196–216.
- S. Chien, B. Cichy, A. G. Davies, D. Tran, G. Rabideau, R. Castano, R. Sherwood, D. Mandl, S. Frye, S. Schulman, J. Jones and S. Grosvenor (2005a) An Autonomous Earth-Observing Sensorweb, *IEEE Intelligent Systems*, 20, no. 3, 16-24.
- S. Chien, D. Tran, G. Rabideau, S. Schaffer, D. Mandl, S. Frye, "Timeline-based Space Operations Scheduling with External Constraints," *International Conference on Automated Planning and Scheduling*, Toronto, Canada, May 2010.
- A.G. Davies et al., "Monitoring Active Volcanism with the Autonomous Sciencecraft Experiment (ASE) on EO-1," *Remote Sensing of the Environment*, vol. 101, no. 4, 2006, pp. 427–446.
- A. G. Davies, S. Chien, R. Wright, A. Miklius, P. R. Kyle, M. Welsh, J. B. Johnson, D. Tran, S. R. Schaffer, and R. Sherwood, "Sensor web enables rapid response to volcanic activity," *Eos*, vol. 87, no. 1, pp. 1–5, 2006.
- A. J. Harris, Flynn, L. P., Dean, K., Wooster, E. M., Okubo, C., Mougini-Mark, P., et al. (2000). Real-time satellite monitoring of volcanic hot spots. *Geophysical Monograph*, vol. 116 (pp. 139–159) pub. AGU.
- R. Huang, M. Xu, N. Peterson, W. Song, B. Shirazi, R. LaHusen, J. Pallister, D. Dzurisin, S. Moran, M. Lisowski, S. Kedar, S. Chien, F. Webb, A. Kiely, J. Doubleday, A. Davies, D. Pieri, "Optimized Autonomous Space In-situ Sensor-Web for Volcano Monitoring," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 2010.
- EOS - Earth Observatory Image of the day, <http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=46693>
- S. Jones, "Analyzing global coverage of an autonomous worldwide sensorweb," *Summer Undergraduate Research Fellowship Final Report*, California Institute of Technology, 2010.
- Schölkopf, B., & Smola, A. J. (2002). *Learning with kernels*. Cambridge, MA: MIT Press.
- Wright, R., Flynn, L. P., Garbeil, H., Harris, A., & Pilger, E. (2002). Automated volcanic eruption detection using MODIS. *Remote Sensing of Environment*, 82, 135–155.
- Wright, R., Flynn, L. P., Garbeil, H., Harris, A. J. L., & Pilger, E. (2004). MODVOLC: Near-real-time thermal monitoring of global volcanism. *Journal of Volcanology and Geothermal Research*, 135, 29–49.

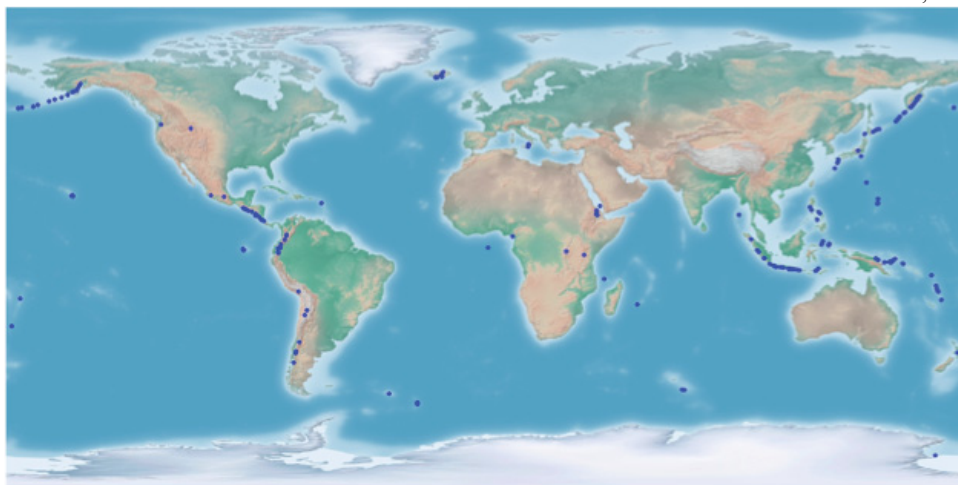


Figure 8: Geographical distribution of Volcano Targets acquired by Volcano Sensorweb 2004-2010 (Map Credit P. Campbell, EO-1 Mission Science Office).